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EVALUATION OF THE STRUCTURAL BEHAVIOR OF TEXTILE COVERS SUBJECTED TO VARIATIONS IN WEATHER CONDITIONS

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INTRODUCTION

A simplified model of an anticlastic membrane is that of two perpendicular ropes, which meet at a point. If the ropes are tensed in opposite directions, the meeting point becomes is fixed. As we increase the tension in the two ropes, more and more force will be required to move the meeting point of the two ropes. In other words, the system becomes more rigid when the tension of the ropes is increased and when applying an external force it will deform less.

The tension applied to a cable system or an anticlastic membrane for it to become more rigid is called pretension. *A membrane or anticlastic net has an adequate structural behavior only if it is in a tensed state.*[1]

Loss of pretension reduces the rigidity of the system, increasing its deformation due to external loads. If loss of pretension exceeds certain limits, the membrane will start to flutter or will be deformed, with the risk of accumulating water or snow, in both cases compromising the durability of the membrane. Therefore, it is of utter importance to know and be able to predict the process of loss of pretension in order to establish maintenance plans that allow optimal levels of initial tension in the anticlastic structures, avoid that loss of pretension reaches critical levels. Loss of pretension is due to the natural behavior of the material, but additionally, there are external factors that influence loss of pretension of the membranes, among these, we can mention the weather as a factor that affects tensional life of membranes.

In this work we will try to prove this hypothesis. In order to do this, the first stage will be the development of a trial bench that allows us to study the effect of superficial temperature, humidity and wind loads on the loss of pretension. The trial bench can reproduce, in a controlled and independent way, each one of the different variables of interest to this study. It allows us to study these variables in physical scale models and with accelerated cycle processes, which can in less time, simulate the behavior of the membranes in their normal life cycle, lowering the cost of the study. On the other hand, the result of these studies will let us validate a mathematical model that is developed at the same time.

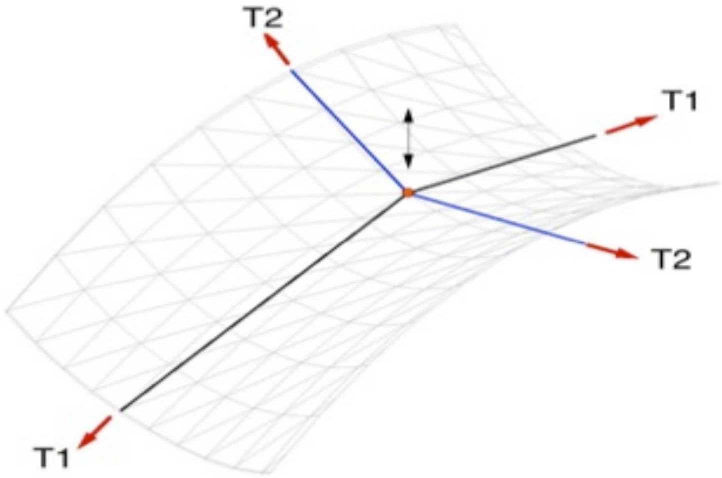


Figure 1: Model

To carry out the trials, it is necessary for the trial bench to be automated, since it must perform in a repetitive manner each of the established cycles, and, likewise, it should include a data acquisition system, which enables it to keep track of how the traction forces on the membrane vary while it is subjected to load and unload cycles, under diverse temperature and humidity conditions.

For the design of the bench, working conditions, the geometry of the membrane, pretension force, temperature and humidity ranges, and wind forces were established in order to dimension the structure of the bench as well as the application and measuring systems.

1. Definition of working conditions

1.1-Weather Conditions:

Working conditions were selected based on the characteristics of the weather conditions defined by the building environmental group of the IDEC of the Faculty of Architecture of the UCV. [2].

In order to determine the superficial temperature, extreme factors of temperature, insolation and wind speed, that rarely occur simultaneously in Venezuelan territory, but which allowed us to establish the maximum extreme of superficial temperature. (Table 1)

Determination of superficial temperature:

Tsun- Tair= Tair + (α Es- hr (10°C))÷hcr [4]

α= 0,2

hcr = 15 Watts/m^2 °C Thermal conductivity

hr= 5 Watts/ m^2 °C Radioactive Exchange coefficient

Es= 1000 Watts/ m^2

T= 35°C

Temperature in maximum insolation conditions 45-50°C, little wind and maximum temperature.

WORKING RANGES		
	Minimum	Maximum
Forces	40Kg/ m^2	75Kg/ m^2
Wind speed		120 Km/h
Temperature	30°C	50°C
Humidity		80%

Table 1: selected working conditions

1.2- Geometric/Structural Conditions:

A virtual model was built to determine the resulting forces, required pretension, and the geometry that will allow us to build the physical model.

For this we used the EASY program (by Technet), where nets for paraboloids were built, with the following characteristics: 0.90x0.90 mts and 1.80x1.80 mts with Sag/Span relations of 1:5, 1:15. FIG. 2. They were loaded with vertical loads of 40 Kg/m^2 both in pressure and in suction (based on ranges previously determined in the weather conditions for the areas that would be studied). FIG. 3.

In the model a 300X300 reticle was set in, where vertical loads and node deformations were calculated, which will allow us to place the burden in the trials where the wind loads are applied. TABLE 2. The model allows us to define the pattern design for the construction of the physical model of the same geometry of the virtual model.

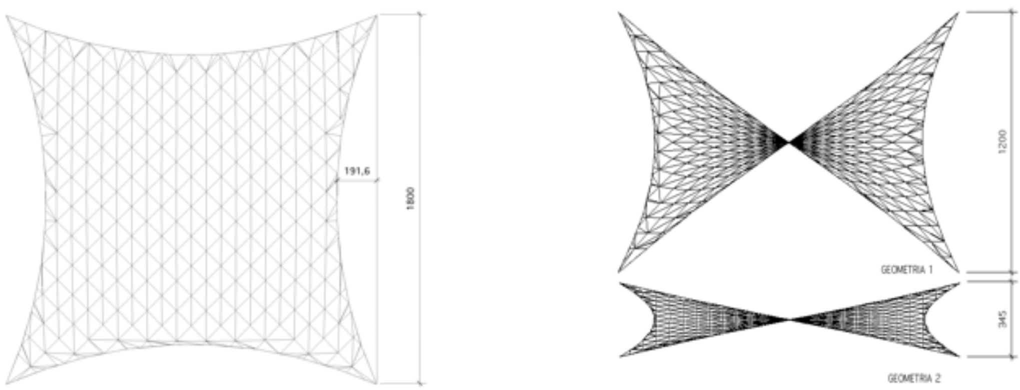


Figure 2 : Geometry of the paraboloids of relations Arrow/light 1:5(Geom.1), 1:15 (Geom.2).

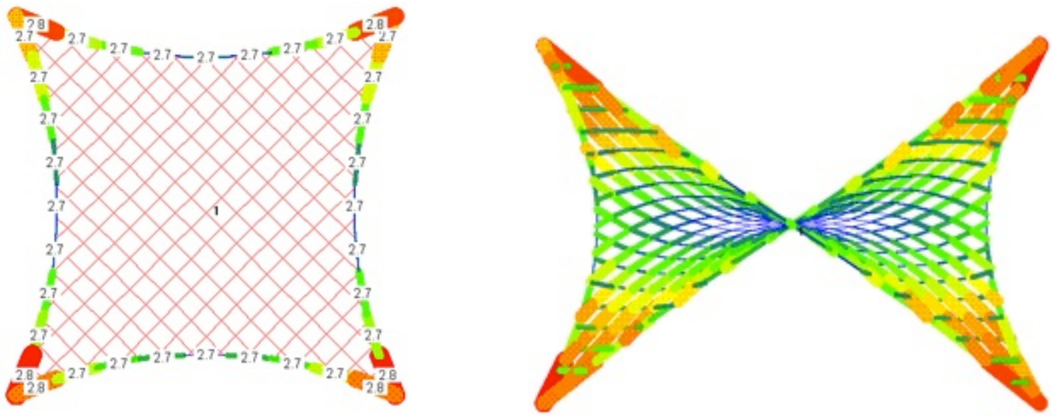


Figure 3. Graphic outcome of the program, which show resulting forces in the edge reinforcement and on the surface of the membrane on the right.

2. Design of the trial bench and data acquisition system:

The work bench is designed based on the previously established conditions. This allows it to hold a small membrane of approximately 2.8 m^2 with changeable Sag and space to house the various devices required to simulate the different trial conditions as well as the measuring equipment.

The supporting structure consists of a not easily deformable square base prism-shaped frame built with ECO(1) 100X100 mm tubular structures, welded at the edges The frame has adjustable legs that allow it to be leveled. (FIG. 4). Metallic bases are fixed on the studs of the vertical edges for the membrane to be connected. These bases are adjustable so as to produce paraboloids of Sag/Span relations 1:5, 1:10, 1:15. (FIG.5)

A second structure is added to this basic frame. This structure is shaped like a table, and contains the mechanism for the wind application system. When necessary it is fixed to the basic frame by means of four bolts.

GEOMETRY	LOAD	RESULTING EXTREMES KN	FORCE ON THE MATERIAL U/T KN	DEFORMATION MTS
1	PRETENSION	5,3	0,1/0,1	
1	40 KN	6,1	0,1/0,2	0,01
1	80 KN	6,2	0,1/0,2	0,01
2	PRETENSION	4,4	0,1/0,1	
2	40 KN	5,4	0,1/0,2	0,03
2	80 KN	7,1	0,1/0,3	0,03

TABLA 2: Summary of results

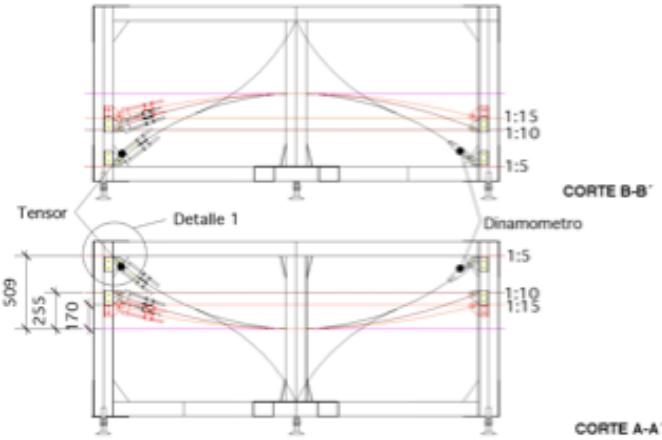


Figure 4 : supporting structure. Figure 5 : bases are adjustable so as to produce paraboloids of different Sag/Span relations .

2.2- Introduction of the tension and measurement

The connection of the membrane with the structural frame is carried out through an element that allows the introduction of the tension (tensor) FIG. 7 and by means of a load cell. The tensors are placed, one in the extreme of the paraboloid that is the highest in relation to the horizontal base plane (high point) and the other in the extreme perpendicular to this one that is placed in a low point of the paraboloid. The load cells are placed in the extremes opposite the tensors. In both cases the terminals allow two degrees of freedom to ensure a perfect alignment, also ensuring there will only be axial loads on the tensors and load cells. The system permits the introduction of traction loads of up to 2400 Kg.

In order to measure the traction loads on the tensile structure, (FIG.6) HBM (brand) Type S load cells capable of measuring up to 1360,77 Kg. (3000 lb.) are used. These load cells may exceed their maximum load up to 120%. These cells use stain gauges placed in a Wheatstone bridge shape, which detect the deformation suffered by the cell and report it in an analogical manner in an equivalent to the force applied in a relation of 3mV per feeding Volt, with a 3 mV/V sensitivity, the operating temperature range is from -30 a +70 ^{o}C. The cells are connected to a signal conditioning circuit, made up basically by an instrumental amplifier, with low-pass filter (fc = 50 Hz) and high quality tension reference, and to an analogical entrance for a USB-6009 data acquisition module, that allows the computer to pick up the load data. [6]

2.3- System for wind load application:

The main problem to reproduce the load applied by the wind is the homogeneous distribution of the load on the membrane surface. Several methods were studied; having chosen the one that was easiest to apply and at the same time provided the most homogeneous load distribution. In the chosen method, the wind load is applied through an air mattress rested against the membrane.

A table-like structure is connected to the main frame of the bench. Inside the structure there is a metallic frame to which a rigid surface has been fixed (a chipboard plate). This frame hangs from the main structure through a collapsible system (FIG. 8) made of articulated bars, which limit the horizontal movement of the frame, but at the same time allow vertical movement, thus ensuring that the frame will remain horizontal during the entire route. The movement of the plane is carried out with the aid of a linear actuator (Dynamat) with a 3KN thrust capacity at a speed of 10mm/sec, placed in the center of the frame and main structure. This engine applies the required force. The applied force is measured with a load cell placed between the linear actuator and the frame. A table-like structure is connected to the main frame of the bench. Inside the structure there is a metallic frame to which a rigid surface has been fixed (a chipboard plate). This frame hangs from the main structure through a collapsible system (FIG. 8) made of articulated bars, which limit the horizontal movement of the frame, but at the same time allow vertical movement, thus ensuring that the frame will remain horizontal during the entire route. The movement of the plane is carried out with the aid of a linear actuator (Dynamat) with a 3KN thrust capacity at a speed of 10mm/sec, placed in the center of the frame and main structure. This engine applies the required force. The applied force is measured with a load cell placed between the linear actuator and the frame.

Figure 6: Load Cell

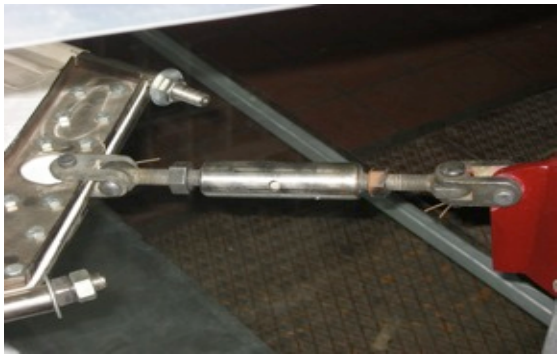


Figure 7: Tensor

A mattress made of vinyl is hung on the surface of the movable frame. This mattress is partially filled with air, so that when it touches the surface of the membrane it adopts its form. As the distance between the frame and the membrane decreases, the pressure inside the mattress increases, transmitting the force that the engine applies to the mattress—through the movement of the rigid plane—to the membrane in the form of pressure. The pressure is normal at the surface and equal per area unit, which ensures that the force is applied homogeneously and in the same manner as in the computer model. [8]

2.4- Temperature application system:

Since the aim is to reproduce the superficial temperature produced by the amount of insolation and not the temperature of the environment, we discarded convection heating systems, in which air surrounding the membrane is heated, and chose instead a radiation heating system, which allows the surface of the membrane to be heated without heating the environment. The chosen system consists of sixteen (16) infrared 250-Watts industrial lamps (FIG. 10), which have a total maximum power of 4000 Watts. The lamps are placed under.

Figure 8: Mechanism to maintain the horizontality of the frame

Figure 9: Mattress

The tensile structure to cover an area of 2.4 m^2. With infrared radiation, the radiated heat can be directed very accurately, avoiding loss of energy, which renders this method very effective. Due to the tridimensional geometry of the membrane, an adjustable base was used to keep the distance and the perpendicularity between the lamp and the membrane. The regulation of the lamps allows us to take the superficial temperature to 60°C. [6]

A control system was designed to allow uniform heating of the surface. The lamps are separated into four independent circuits, each one controlled by a sensor (digital dual temperature/humidity sensors), placed under the membrane in pockets to avoid direct exposure of the lamps, and in the center of the action area of the corresponding circuit, producing four independent control bows. The system allows the control of the amount of power given to the lamp, managing to make it radiate the necessary amount of energy at all times so that the temperature in the surface remains stable. The control system can compensate the effect of the Lamp/membrane distance difference and can even allow the compensation of the cooling effect due to air currents. Although the system remains closed during the trials, all the faces [sides] of the bench were open during the adjustments to the control system in order to make the access easier. The lamps facing the air current was turned on more frequently, than the ones that were further away, to compensate the cooling, thus ensuring uniform temperature throughout the entire surface. The heating period of the membrane to 50 °C is 3 minutes. To accelerate cooling, an extractor is used. Air extraction takes place at a rate of 11.4 m^3/min, air injection 8.6 m^3/min (power: 40 Watts), which allows the total volume (2.6 m^3) to be changed in 54 seconds. The extractor is activated through triac controlled from the computer. The environment temperature is recorded with a digital sensor connected to the control system and allows environment temperature to be recorded independently from the membrane temperature.

2.5 –Humidity Application System:

Humidity is varied by introducing water in the form of fog by means of a fogger inside the same isolated system used for the temperature trials. For this, a linear engine or *plunger* is used. It works (opening or closing) a multifunction hose-tip fogger (FIG. 11). Humidity is measured inside the box through dual integrated sensors, which send the information in a digital manner to the computer that adjusts the fogging time and temperature necessary to reach the level of humidity (80%). To shut down the cycle, the extractors and the lamps are activated to take out the humid air and take humidity to the environment level.

2.6 – Automatic Control System:

The trial bench should work for long periods under little human supervision. In case the process stops abruptly, the supervision system must automatically store data of interest for the process, and it must be ensured that the system will not go haywire in case of power failure or loss of communication." [6]

The control of the bench is carried out with a computer equipped with a data acquisition card from National Instruments model USB 6009. The control system is complemented with three PIC18 micro controllers, which receive the data from the sensors (dual digital sensors), the orders from the computer, and activate the various devices, which is done through triac that supply the lamps, extractors, etc. with power.

Figure 10: Infrared Lamps.

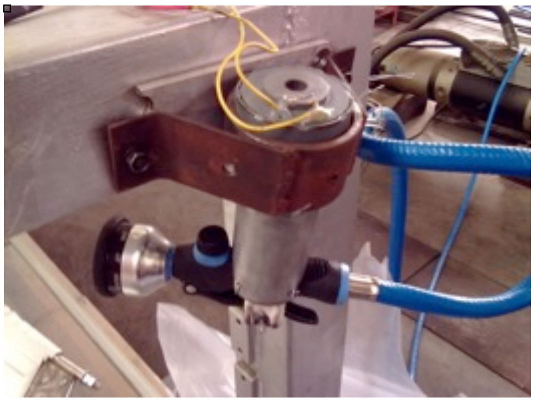


Figure 11: Fogger with Plunger

There are two power modules: the high power module, responsible for the heating system and the power module used for handling the devices of the process, such as actuators or diffusers. The system allows the acquisition of temperature, humidity, and tension data. In figure 12 you may see a block diagram of how the various sections that compose the modules interconnect.

3. Trials

3.1 – Test Samples

The membrane is made according to the pattern design obtained from the informatics model (EASY program). Its geometry is a symmetric hyperbolic paraboloid that measures 1800mm on the side (for the first trial group with a Span/Sag ratio of 1:5, geometry 1).

The pattern cutting is carried out in such a manner that when the weave and the warp are ensambled, they are placed in the same direction in the four patterns, to ensure uniformity in the behavior and so that all the Test samples are comparable. The membrane is reinforced at the edges with a 6 mm 6x19iwrc, steel cable [edge reinforcement] with stainless steel terminals, threaded at the tips. All of this is placed in an edge pocket. On the vertexes, the membrane ends in identical corner plates that trap the extreme of the membrane and receive the steel cables of the edge reinforcement. A pocket is added to the membrane with a plastic bar to keep it from slipping. The corner plates, as well as the edge reinforcement, are removable, and are used in all the membranes that will be tested. The corner plates are built with two pieces made in a 1 mm sheet of stainless steel, folded at the edges. The tubes that permit the steel cable to be passed are welded to one of the pieces. (FIG. 13)

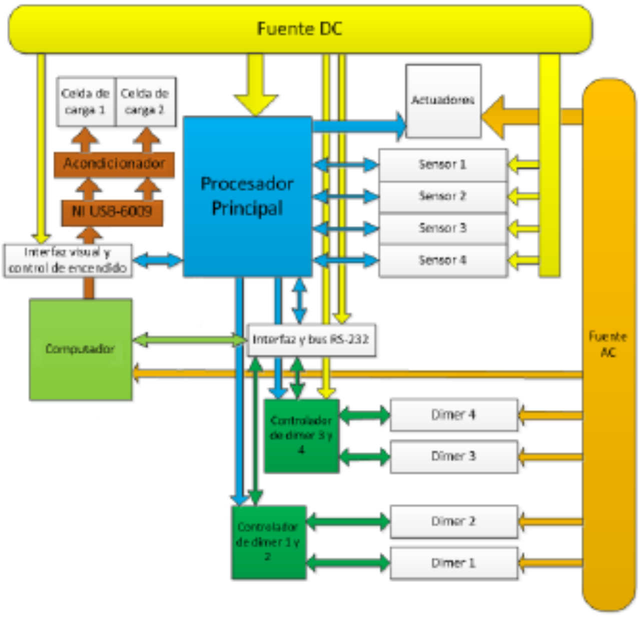


Figure 12: Structure of the hardware

3.2 – Trials of the equipment

Trials with the systems were carried out to verify that it behaved according to the specifications of the design and the virtual simulations that were carried out during the design of the control circuits and that were robust enough to withstand long working periods.

Rehearsal routines were programmed for the temperature system for it to carry out several cycles, using the temperature of the environment as minimum and taking the membrane up to 55 ºC. In graph 1 the system's behavior is shown. The black line reflects the temperature of the environment on the membrane, measured by each one of the sensors. Similar behavior is seen in the various sensors. The differences are in the slope to reach the maximum and minimum values as rapidly as possible.

Regarding humidity, rehearsals were carried out to perform cycles of 30% to 55% of humidity. The system's behavior is shown on graph 2, where the lack line represents humidity inside the rehearsal bench and colored lines the humidity on the membrane, recorded through the various sensors. The variation is due to the differences in location of the sensors in relation to the fogger and the extractor, mainly affecting initial measurements. The system takes humidity to the maximum established value, regulating the average humidity inside the bench.

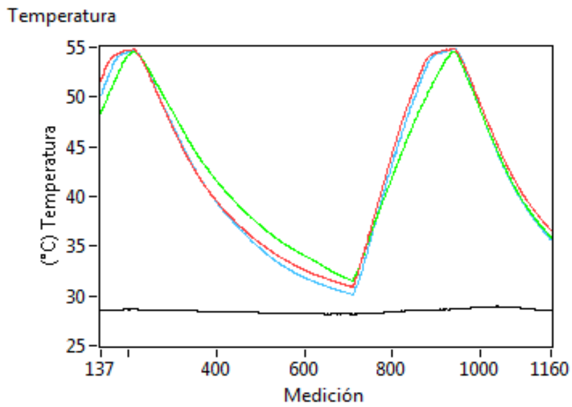
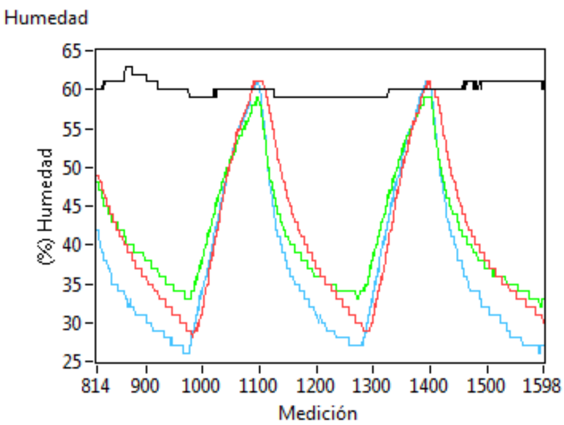
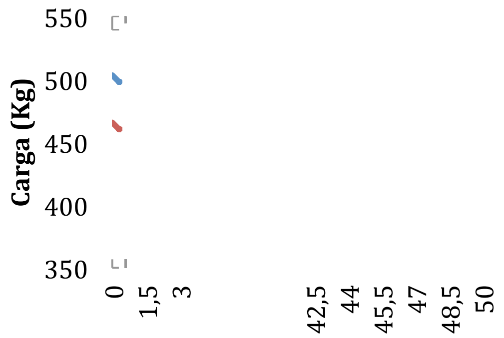


Figure 13: Test tube

Graph 1. Behavior of the temperature

As for the load measurement of the loads, these behave in the expected way, increasing when the temperature decreases (contraction of the material) and lowering when the membrane is heated (expansion of the material); and, on the contrary, when humidity decreases, the load decreases and vice versa.





Graph 2. Behavior of humidity

Graph 3. Loss of the Pattern's pretension

3.3 – Pattern

A new membrane is placed on the trial bench, it is taken to a pretension of 440 Kg, pretension is allowed to drop for 15 minutes and is pretensed again to the previous load. The membrane is left on the bench for 36 days with no further manipulation. The tension on the load cells, the environment temperature, and humidity were measured. With this pattern it is possible to establish the process of loss of pretension due to the material's characteristics.

Graph 3 reflects a rapid fall in pretension; pretension rises when tension is applied a second time and then starts to decrease, until it becomes stable at 80 hours. This rapid fall occurs because of the fiber's readjustment inside the membrane (creep), loss of pretension will continue very slowly, only affected by changes in the environment temperature between day and night in the structure laboratory.

CONCLUSIONS

- The trial bench allows rehearsing Hyperbolic Paraboloids of a 2.8 m^2 area with Sag/Span ratio of 1:5, 1:10, 1:15. It allows the application and measurement of tensions of up to 1360.77 Kg with an accuracy of +-1 Kg.
- It allows heating the membrane by means of radiation in a uniform manner from 20ºC to 60ºC and returning to environment temperature in 30-minute cycles; for the maximum working temperature, the cycle can be performed in 25 minutes or 57 cycles per day.
- Humidity in the bench can be kept in a range of 20% to 80%, and it is possible to carry out entire cycles in 12.5 minutes.
- The bench allows us to take the membrane to the conditions and in the ranges established in the working conditions.
- The rehearsed membrane establishes the pattern of loss of pretension due to the readjustment of the fibers in the material. Its incline allows us to extrapolate this loss in a bigger time frame, and will allow us to compare the loss when other conditions are applied.
- At the time this paper was written control system of the mechanism for simulation of the wind force have not ended and temperature and humidity rehearsals are being carried out.

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